Measuring auditorium seat absorption

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There is a need for a more accurate laboratory measurement method to predict auditorium seat absorption. The traditional method tends to overpredict the absorption of the exposed front and sides of seating blocks. An alternative reverberation chamber method was studied that involves the use of barriers to obtain realistic measurements of front and side absorption. This method was validated by comparing measurements of seats made in a reverberation chamber with *in situ* absorption data for the same seats, calculated from reverberation time measurements in ten auditoria with and without the seats present. The accuracy of the alternative method was satisfactory in all cases, although a severe lack of diffusion in two of the halls hindered the validation process. It was found that using a frequency-constant edge correction strip to account for side and front absorption could lead to significant errors in auditorium absorption prediction.

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INTRODUCTION

Of all the parameters in common use in auditorium design today, reverberation time (RT) was the first to be established and it is one of the most subjectively important. Because the RT in a hall is dominated by the absorption of the seating and audience, it is essential that these can be measured or predicted accurately in the early stages of design. However there is currently no wholly accepted standard test method for measuring seating absorption and the data quoted in the literature vary widely.

The traditional method of measuring seating absorption involves placing a small array of seats in the centre of a reverberation chamber. The main problem with this arrangement is that it exaggerates the absorption of the exposed front and side of the seating array, compared to the larger seating blocks commonly found in auditoria. This results in errors in the predicted auditorium RT.

A modification of the traditional reverberation chamber test method for seating absorption was proposed by Kath and Kuhl as long ago as 1964.[1] Though this seemed to offer the possibility of greater accuracy by correctly allowing for the absorption of the exposed front and sides of seating blocks in auditoria, it has not been widely taken up. This may have been due to the absence of any large-scale validation of the method, and a lack of understanding of the effects of the various measurement parameters. The work reported here aims to clarify this situation.

This paper covers the investigation and validation of a reverberation room method of measuring seating absorption. First, the available measurement and prediction methods are briefly reviewed. Then, data on the effects of parameters of the measurement method are presented. The choice of the optimized parameter values is justified by comparisons between reverberation chamber measurements and accurate *in situ* seating absorption measurements in ten auditoria.

I. THE AVAILABLE METHODS

A. The required accuracy

Several authors[2,3] have remarked upon the need for greater accuracy in the prediction of auditorium absorption coefficients. The question arises here of how much accuracy the designer needs. An estimated answer can be given from the difference limen for reverberation time T obtained by Seraphim (Ref. 4, pp. 505–507). Seraphim measured the smallest percentage change $\delta T/T$ that could be correctly identified by 75% of his subjects for reverberated bandpass noise with various values of T and center frequency. For the midfrequency octave between 800 and 1600 Hz, $\delta T/T$ is between 3% and 4% for values of T between 0.6 and 4 s. Of course, $\delta T/T$ is likely to be different for different source signals, so it is unfortunate it has not been measured with music. The difference limen is likely to be larger for music, so we might assume a figure of 5%. Since the RT in a hall is largely governed by the audience and seating absorption, one should aim to measure seating absorption to an accuracy of 5%, at least at midfrequencies.

B. Averaged data

Beranek[5] and Kosten[6] have both produced data for the average absorption coefficients of occupied and unoccupied seating. The data were averaged from measurements in many halls and are useful for estimating RT in the early design stages. Beranek showed that greater accuracy is obtained by calculating seat absorption coefficients based on absorption per unit floor area rather than by the previously accepted absorption per seat. Most subsequent seat absorption work, including that validated here, has used this sort of coefficient. However, the use of average data is not reliable for finished designs unless one can be confident that the seats to be used in a particular hall will have an absorption close (within 5%)

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to Beranek's or Kosten's average. Since modern seat designs can vary greatly, this will typically be doubtful.

C. Standard measurement methods

If we cannot very accurately predict the absorption of a particular area of chairs using the above methods, then we must measure the chairs. Currently, this is done using a small sample of chairs in a reverberation chamber, though an attempt has been made to devise a method of predicting the absorption of chairs from the measured absorption of their component parts.[7]

The aim of measuring the random incidence absorption of a small sample of seats in a reverberation chamber is to predict the absorption that a large area of the same seats will exhibit when installed in an auditorium. The usual method is to place a rectangular array of the seats near the center of the reverberation chamber, using the same row spacing as is found in the real theatre. Standard sample areas vary from[8] 6.69 m^2 to[9] 10–12 m^2. Hence the largest typical sample is likely to be about 24 chairs; in the current work, the standard sample was four rows of six chairs. When this is scaled up to a large block of seats every fourth row is in effect a front one, and every sixth seat is on the edge of an aisle. This overemphasis of the absorption of the front row and side aisles leads to a predicted absorption higher than that which will be exhibited in the auditorium.

D. Bradley's method

Recently, Bradley[10] published details of a seating absorption measurement method which attempts to take account of the variation of seating absorption coefficient with sample size—the failing of the traditional method. This involves making measurements on five or six differently sized arrays of a seat type. The variation of absorption coefficient with the ratio of array perimeter length to area, E, is assumed to be linear, so that a straight line may be fitted to the data. This is extrapolated back to the smaller values of E that characterize large seating blocks in auditoria. Bradley found that this method could give accurate results when compared with measurements of the same seats *in situ* in auditoria.

Though it seems that this method can offer superior accuracy over the methods discussed above, it does require many tests for each type of seat measured.

E. Kath and Kuhl's method

Kath and Kuhl also thought that the over-valuing of front and side absorption in the traditional method was a major reason for poor prediction of auditorium absorption coefficients. They proposed[1,11] an alternative method that requires fewer measurements than Bradley's and yet may be at least as accurate. In this method the seating array is placed in the corner of the reverberation chamber, and the exposed edges obscured with barriers, as in Fig. 1. Though it seems that the array is mirrored in the adjacent walls of the chamber, thus effectively increasing its size, it is not effectively infinite as Kath and Kuhl thought. Diffraction effects will still be present and so the measured absorption coefficient may still vary with sample size. These effects have been discussed in Ref. 12.

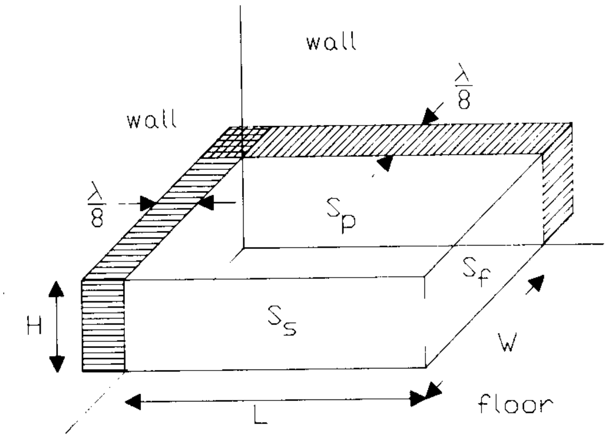

FIG. 1. Schematic diagram of an array of seats in the corner of the reverberation chamber, showing the strips needed to correct for pressure doubling. The subscript "f" indicates the edge of the front row of seats, subscript "s" the edge of the side aisle seats, and subscript "p" the plan area of the seats without edge correction.

This arrangement allows us to measure absorption coefficients for three conditions of the seating array shown schematically in Fig. 1: α_p with barriers covering both the front and side of the array, α_1 with barriers covering the side only and α_2 with barriers covering the front only. These are all related to the plan area S_p shown in Fig. 1. Two absorption coefficients can then be found for the front and side: α_f and α_s; these relate to areas S_f and S_s, respectively, in Fig. 1. If the areas of the front row (S_{fa}), side aisles (S_{sa}) and plan area (S_{pa}) of a particular large seating block in the theatre are known then its absorption coefficient α_m, expressed as the total absorption that would be measured *in situ* divided by the plan area of the large block, can now be predicted with the reverberation chamber absorption coefficients to be

$$\alpha_m = \alpha_p + \alpha_f S_{fa}/S_{pa} + \alpha_s S_{sa}/S_{pa}. \quad (1)$$

Thus α_m should incorporate the correct amount of absorption due to the exposed front row and side aisles.

The corner placing of the seats is advantageous because it increases the effective size of the array. However, there is a disadvantage: The SPL in a reverberant field is increased at the boundaries,[13] so the absorption coefficients measured will be higher than those found when the sample is in the center of the chamber. To compensate for this, Kath and Kuhl proposed[14] that the absorber areas (S_p, S_f, and S_s) used in the calculation should be increased by strips of width λ/8 as shown in Fig. 1, where λ is the wavelength corresponding to the center frequency of the measurement. This extra absorbing area accounts for the increase in measured total absorption due to the increase of up to 3 dB in SPL close to the wall. In a corner, there is an increase of up to 6 dB (see the overlap in Fig. 1), and a correction of $(\lambda/8)^2$ is needed.[1] Hence, the effective test areas become

$$S_p = (L + \lambda/8)(W + \lambda/8), \quad (2)$$

TABLE I. Descriptive data for the ten halls and their seats.

Hall	Use[a]	T_{mid} (s)	N_t	N_m	V (m^3)	S_{pa} (m^2)	S_{sa} (m^2)	S_{fa} (m^2)	N_b	Back rest[b]	Rear back[b]	Squab[b,c]	Under squab[b,c]	Arm rest[b]	α_{mid}
B1	c/mp	1.65	1811	1019	10929	441	68	40	1	CF	metal	CF	metal	···	0.59
B2	c	2.13	702	468	6627	208	26	25	0	CF	wood	CF	wood	CF	0.68
C	mp	1.98	≈1000	616	14543	318	56	17	1	CF	plastic	CF	metal	plastic	0.56
D1	t	0.86	514	514	2488	242	62	12	1	CF	wood	CF	wood	CF	0.67
D2	t	0.88	900	734	3007	301	45	5	2	CF	wood	CF	wood	CF	0.69
G	c	1.97	2500	2500	28750	1386	170	14	1	CF	CW	CF	CW	CF	0.66
H	c/mp	2.02	1150	498	9571	177	29	25	2	CF	metal	CF	metal	···	0.55
L	t	2.21	700	700	12290	340	50	15	0	CF	wood	CF	CW	CF	0.67
M	mp	0.67	624	241	1538	202	15	14	0	VF	metal	VF	metal	···	0.37
O	mp	1.46	669	669	8271	256	44	14	0	CF	metal	CF	wood	···	0.68

[a]c=concert hall, mp=multipurpose hall, and t=theater.
[b]CF=cloth (woven) on foam, CW=cloth (woven) on wood, and VF=impervious vinyl on foam.
[c]The squab is the padded horizontal part of the seat which is sat on.

$$S_s = LH + H\lambda/8, \quad (3)$$

$$S_f = WH + H\lambda/8, \quad (4)$$

where all the symbols are defined in Fig. 1.

II. VALIDATION METHOD

It was decided to attempt to validate Kath and Kuhl's method by carrying out absorption measurements on seating *in situ* in auditoria and on samples of the same seats in a reverberation chamber. This was done for ten auditoria, so that RT measurements were made in all ten with the seats present and with as many as possible removed.

The reverberation chamber used has a volume of 224 m^3 and a surface area of 226 m^2. It has one slanting wall to aid diffusion; the ceiling is horizontal. Eleven fixed, curved diffusers with a total two-sided area of 67.1 m^2 were suspended in the room. Two loudspeaker positions and ten microphone positions were used to obtain average RTs. Sabine's formula was used to calculate the absorption coefficients. The measurement system used in both the laboratory and the auditoria centered on a Norwegian Electronics real-time analyzer (type 830).

The auditoria were of various types: Some were multipurpose halls in which a significant portion of the seating could be removed; others were newly built or refurbished. All data reported here are for unoccupied auditoria. Considerable efforts were made to ensure that each auditorium changed as little as possible between the two RT measurements, though it was usually necessary to make some allowance for areas of carpet or curtains being added or removed. In some of the multipurpose halls, it was possible to make the "full" and "empty" measurements on the same day, so that nothing significant changed apart from the seats. Any necessary corrections for air absorption were made based on relative humidity and temperature measurements made during the RT test.

Table I lists some descriptive data for the seats and halls. Three categories are given for the hall usage: Concert, multipurpose, or theater. T_{mid} is the average of the RTs in the 500- and 1000-Hz octave bands in a hall with all the unoccupied seats present. Here, N_t is the seating capacity, but N_m is the number of seats that were measured; i.e., the number that could be removed from a hall or the number that were installed if the hall was being built or refurbished. Additionally, V is the volume of the auditorium, S_{pa} is the total plan area of the N_m seats, and S_{sa} is the total area of the sides of all the blocks of seats comprising N_m that are exposed to the sound field. Similarly, S_{fa} is the total area of the front rows of all the blocks of seats comprising N_m that are exposed to the sound field. If the front row of a balcony block was obscured by a balcony front, then it was not counted for S_{fa}. Here, N_b is the number of balconies. Table I also lists the materials forming the major components of the different seats. α_{mid} is the mid-frequency (average of 500- and 1000-Hz octaves) value of α_p measured in the reverberation chamber.

III. SOME REVERBERATION CHAMBER FINDINGS

During the validation process, many reverberation chamber measurements were made to investigate the effects of varying parameters of the method. The effects of sample position, sample configuration, occupancy and carpet are reported in detail elsewhere.[15] Some of the more interesting findings are summarized here. Because of time limitations, it was not possible to examine the effect of every combination of parameters on each seat type. However, most parameters were investigated for most seats, using an array of four rows of six in almost all cases. Occupied measurements were made on two seat types.

Since only the effects of the various parameters are discussed in this section, most of the following graphs use a standard measurement as a baseline: The seats were placed in the corner of the chamber, at a 900-mm row spacing, surrounded by barriers 900 mm high, corrected for pressure doubling at the walls, but with no corrections for front and side absorption. The barriers were constructed from sheets of 18-mm chipboard.

A. The spread of absorption coefficients

Figure 2 shows the range of absorption coefficients from the ten seat types that were measured in the standard configuration. Most of the seat types have an absorption profile not unlike that of a homogeneous porous absorber. The most notable exceptions are seat types D2 and M. D2 was a stan-

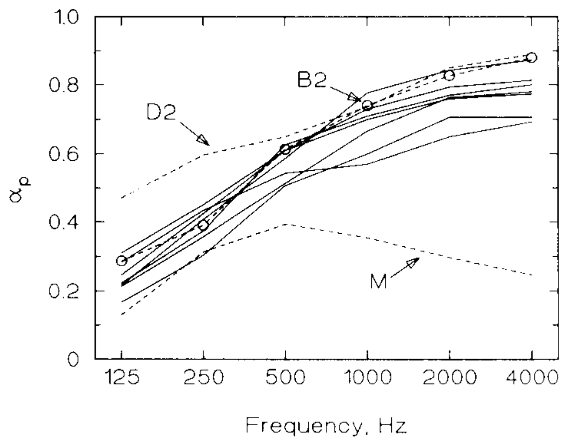

FIG. 2. Reverberation chamber absorption coefficients of ten different seat types, measured using the "standard" version of the new method.

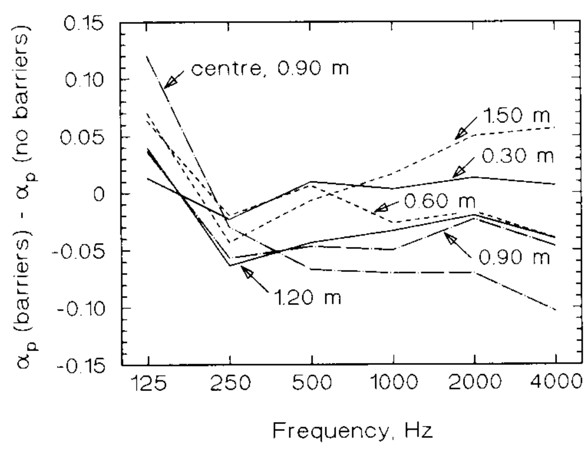

FIG. 4. Difference caused by barriers of different heights to the α_p of an array of 24 seats of type H, measured at 800-mm row spacing. One line is for the seats in the center of the chamber, the rest are for the seats in the corner.

dard well-upholstered model, except that its squab was hollow. Under the cushion, this squab consisted of 18-mm chipboard, then a 45-mm air gap, and then 5-mm plywood. This seems to have produced an effective low-frequency resonant panel absorber. Seat type M was covered with impervious vinyl, limiting its high frequency absorption severely. Seat type B2 is picked out as representative of the well-upholstered cloth-covered seats often installed in concert halls. It was a standard model from a large manufacturer.

B. Row spacing

Figure 3 shows the effect on the absorption coefficient of seat B2 of varying the row spacing over a small range commonly found in auditoria. The effect is significant compared to the magnitude of one standard error. It should be noted that increasing the row spacing increases the total absorption of the seat array, but the plan area increases faster, and so the combined effect is to decrease the absorption coefficient.

Though the lines in Fig. 3 are different, they are all highly correlated with each other (the lowest correlation coefficient is 0.9938). This indicates that it should be possible

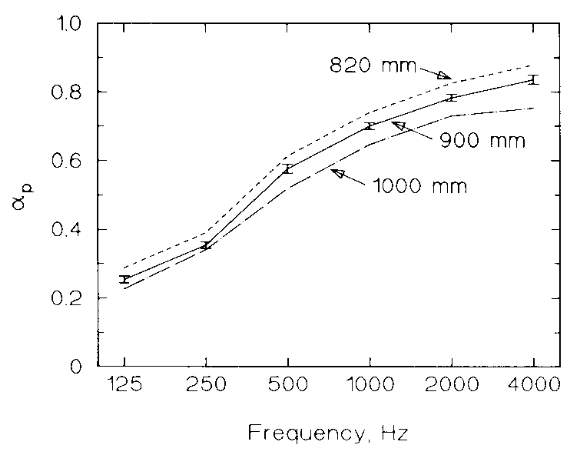

FIG. 3. Effect of row spacing on the α_p of an array of 24 seats of type B2, measured in the corner and surrounded by 0.9-m barriers.

to predict absorption at one row spacing from a measurement of absorption at another. No attempt has been made to produce a straight line regression for prediction, however. The magnitude of the effect of row spacing depends, not surprisingly, on how absorbent the seats are. Hence, if figures are available for the absorption of particular seats at two different row spacings and a hall designer requires data for a third spacing, then linear extrapolation should be a good first approximation.

C. Barrier height

One aspect of Kath and Kuhl's method that has caused some confusion in the literature is the question of specification of the barrier height. To investigate the influence of barrier height, measurements were made on some relatively lightly upholstered seats, from hall H. These seats are 840 mm high. Modular barriers were used, in the form of sheets of chipboard 300 mm high and 18 mm thick. The barrier surface was left untreated. The results are shown in Fig. 4, presented as the difference in α_p caused by the barriers. Consider the mid and high frequencies for the seats in the corner of the chamber first. When the barrier height is increased from 0 to 300 mm, there is little difference in α_p because a 300-mm barrier obscures only the nonabsorbent chair legs (these seats did not have a tippable squab). As the barrier height is increased from 300 through 600 to 900 mm, though, α_p decreases first at high and then at mid frequencies. Now the barriers are progressively obscuring the absorbing surfaces of the squab and back of the seats.

When the barrier height is increased from 900 to 1200 mm there is little change in α_p at mid and high frequencies. This seems reasonable, since there are no more absorbing surfaces on the front and side of the array to be covered. With an increase to 1500 mm, however, there is a significant jump in α_p at mid and high frequencies. The barriers are now some way above the seat tops, so it is possible that the absorbing array is no longer in a diffuse field. As the barriers are extended further and further above the absorber, any sound rays entering this enclosure are less likely to leave, and so the apparent absorbing power of the array will increase. This situation is analogous to that of seating under a deep balcony overhang. Cremer and Müller (Ref. 4, p. 263) say that such seating is no longer in the diffuse hall field, and recommend ascribing an absorption coefficient of 1.0 to the opening under the overhang, as one might to an open window. The high frequency absorption at 1500 mm is also probably due in part to the surface absorption of the untreated chipboard.

There is also evidence of an increase in low-frequency absorption due to the barriers in Fig. 4. The most obvious possible causes are that the barriers act as panel absorbers or that the enclosure they form around the seats contributes extra absorption. If the measurement is conducted with the seats in the center of the chamber, the enclosure is similar, but the required number of barriers is doubled. In Fig. 4, the low-frequency absorption of barriers used in the center is roughly double that of barriers used in the corner. Hence, the anomalous absorption seems due mainly to the barriers acting as a panel absorber.

1. Minimizing barrier absorption

The unwanted low-frequency barrier absorption is lessened by using a position in the corner rather than the center of the reverberation chamber for seat absorption measurements. Reducing it further seems more difficult. Because of the panel absorption, it would be advantageous to suppress the most prominent modes in the barrier or move them out of the frequency range of interest. Unfortunately, during this work, suitable materials were too expensive to buy in an area large enough to form seating barriers.

If the problem cannot be tackled at source, then a crude correction can be made to seating absorption measurements by subtracting the absorption coefficient of the barriers measured separately, from the absorption coefficient of the seats with barriers. This is not entirely satisfactory for two reasons. First, the "barriers only" absorption measurement will not be very accurate due to the low absorption being measured, and so the corrected absorption will also be inaccurate; and second, it takes no account of any possible interaction between the barriers and the seats.

It should be remembered that the barrier absorption problem is not as bad as it might be, since it occurs at the lower end of the frequency spectrum. Low frequency absorption measurements are always less accurate, especially in rooms with less then perfect diffusion like auditoria. Also, fortunately, the human ear is also less discriminating in this region: Cremer and Müller (Ref. 4, pp. 507–509) quote results from Plenge showing that the subjective limen for relative change in RT increases with decreasing frequency below 1 kHz.

The unwanted high-frequency barrier absorption seems easier to deal with: The barriers should be at least as high as the seating plus any auditors, but excessive extra height (say, more than 100 mm above the top of the absorbers) should be avoided. Note that the lowest values of α_p at mid and high frequencies in Fig. 4 are for 900-mm barriers. Since most of the seat types measured in this work were a little below a height of 900 mm, two sets of barriers were commonly used: 900 mm high for unoccupied measurements and 1200 mm high for occupied work.

D. Edge corrections

An awkward problem in measuring the absorption coefficient α of a three-dimensional object in a reverberation chamber is that the measured coefficient is found to vary with the size of the sample. If the absorbing edges of a sample are exposed, then this variation is due to two components: (i) The absorption of the front row and side of the seating array, causing α to increase as sample area increases; and (ii) diffraction of sound waves at the edges of the array, again causing α to increase with area.

In the past, acousticians have usually made an allowance for the absorption of the sides and front of a seating block by increasing the seating area used in calculations from the actual plan area. These corrections usually take the form of a strip of constant width into which the plan area of the seating block is supposed to extend at all its exposed sides. Because the width used is constant with frequency, the assumption is made that the exposed sides have an absorption coefficient proportional to that of the plan area of the block. Also, the same strip width is usually used for the exposed front row and sides, so the absorption coefficients of the front and sides are assumed to be the same. However, even once these assumptions have been made, it is not clear what the width of the strip should be. Most designers use the value advocated by Beranek, which has changed from[16] 1 to[5] 0.5 m.

When the absorption coefficients of the front and side of seating blocks was measured using Kath and Kuhl's method, it was found that the results were quite different from the absorption coefficient of the plan area of the same block. For clarity, these results are expressed as edge correction strip widths k_f and k_s for the front and side of the block, respectively:

$$k_f = L(\alpha_1/\alpha_p - 1), \tag{5}$$

$$k_s = W(\alpha_2/\alpha_p - 1), \tag{6}$$

where the symbols relate to Fig. 1.

Edge correction strip widths were measured for samples of six different seat types (B1, B2, D1, G, H, and L). The range of these data is shown in Fig. 5: The spread is large and the means are far from constant with frequency. If a frequency-constant figure is insisted upon, then 0.5 m seems a better choice than 1 m. Even so, we might expect this approximation to introduce significant errors into the prediction of auditorium RTs. It must be concluded that it is far better to measure the side and front absorption of a sample of seats rather than rely on a frequency-constant edge correction.

The question of how to treat aisles, as opposed to completely exposed sides, remains. If an aisle is 1 m wide, then it seems correct to say that the seats on either side are not fully exposed, due to shading from the seats on the opposite side. If the aisle is carpeted, as it usually is, then sound energy reflected from the floor onto the seats should be less than that encountered in the reverberation chamber. Both

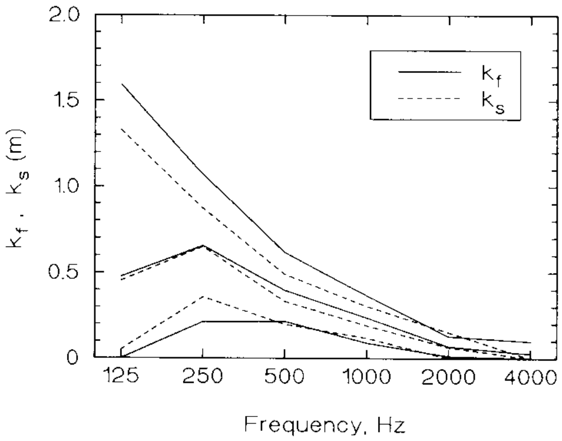

FIG. 5. Minimum, mean and maximum edge correction strip widths at each frequency for the exposed front row (k_f) and the exposed side area (k_s) of six different seat types.

these effects would tend to reduce the absorbing power of the aisle seats, but both will probably be frequency dependent.

IV. COMPARISON OF REVERBERATION CHAMBER AND AUDITORIUM MEASUREMENTS

For each hall, many reverberation chamber measurements produced by combinations of different measurement parameters were compared with one auditorium measurement. The auditorium absorption coefficient was expressed as the total measured absorption attributed to the seats divided by the total plan area of the seating. Across all ten halls there was one reverberation chamber measurement configuration that consistently produced a better agreement than any other:

A rectangular array of seats was placed in the corner of the chamber at the auditorium row spacing and surrounded by unabsorbent barriers 0.9 m high for unoccupied seats and 1.2 m high for occupied seats. The absorption of the plan area was measured and corrected for pressure doubling. Two more measurements were made, with the barriers covering the side and front of the array only. A separate measurement of low-frequency barrier absorption was subtracted from all the data. α_m was then calculated from Eq. (1). In calculating S_{sa} in Eq. (1), the best results were found if aisles bounded by seating on both sides were treated as one exposed side area. The values of S_{sa} in Table I reflect this.

The following sections discuss the comparison for each hall in detail. In each graph, "large finite" refers to α_m calculated as described above, "infinite" refers to α_p and "small" refers to the traditional method with the array in the center of the chamber with no barriers.

A. The concert halls B2 and G

Figure 6(a) shows the comparison for hall B2. As expected, the auditorium absorption coefficient lies between the reverberation chamber data for the "infinite" configuration (which include no side area absorption) and the "small" configuration (which include too much). It is quite well matched by the "large finite" curve.

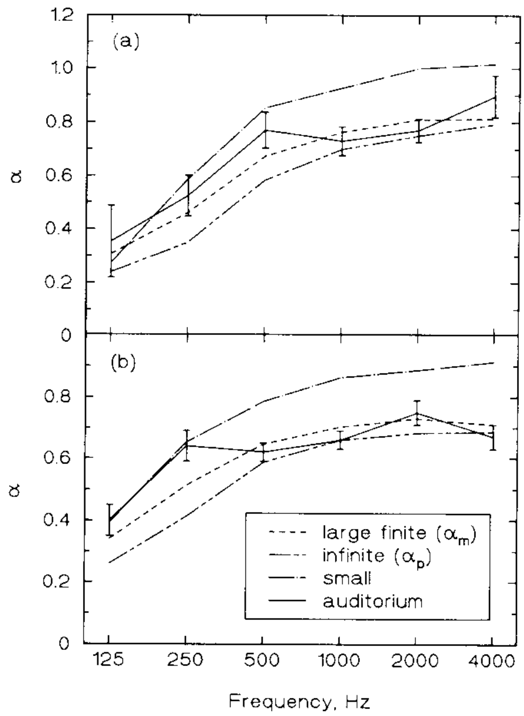

FIG. 6. Absorption coefficient of (a) seating B2 and (b) seating G measured *in situ* in the auditorium and by three different reverberation chamber measurement methods. The error bars represent ± one standard error.

Figure 6(b) shows the comparison for hall G, a large modern concert hall. Again, the auditorium absorption coefficient lies between the "infinite" and "small" measurements. Overall, the "large finite" line is the best match. At high frequencies, the traditional measurement has significantly overestimated the absorption in the hall. The measurement was performed with a 24 seat sample; with smaller samples the excess would be even greater. At low frequencies, particularly 250 Hz, the "large finite" data are significantly lower than the auditorium data. This was probably caused by wood paneling being added to the hall during construction. Though it was difficult to police the construction schedule completely, approximately 300 m^2 of paneling over an air gap was added between the two RT measurements. No absorption data are available for the particular panels used, but coefficients of 0.50 at 250 Hz (Ref. 17) or 0.42 at 125 Hz (Ref. 5) suggest that about 150 m^2 of total absorption was added. This would account for an extra 0.11 in the auditorium absorption coefficient at 250 Hz in Fig. 6(b).

B. The concert/multipurpose halls B1 and H

The agreement between the "large finite" reverberation chamber data and the auditorium data is very good for hall H, as Fig. 7(a) shows. Again, the auditorium line lies between the "infinite" data (which include no side absorption), and the "small" data (which include too much side absorption). The accuracy of this measurement was compromised by the fact that only 43% of the seats in the hall were re-

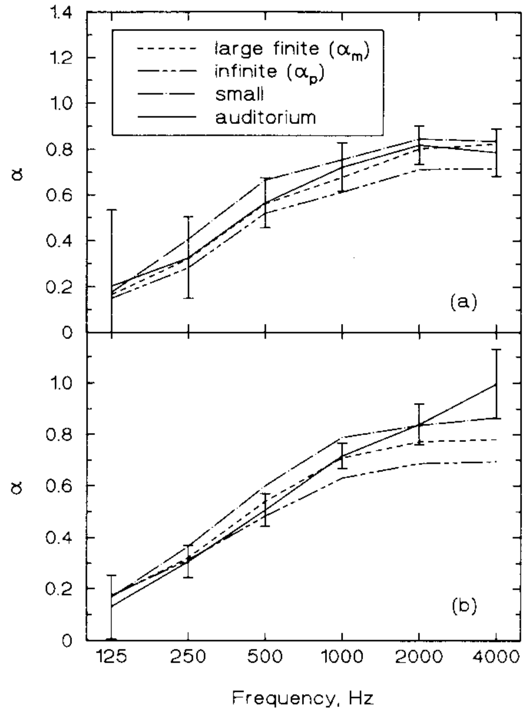

FIG. 7. Absorption coefficient of (a) seating H and (b) seating B1 measured *in situ* and by three different reverberation chamber measurement methods.

movable. Nevertheless, the reverberation chamber measurement has accurately predicted the average absorption coefficient of the seats in the hall.

For the other large concert/multipurpose auditorium, hall B1, the agreement is good at low and midfrequencies, as shown in Fig. 7(b). At these frequencies, the auditorium line lies between the extreme reverberation chamber lines, suggesting that it is a reasonable result from a diffuse sound field. At 2 kHz and particularly at 4 kHz, however, the seat absorption in the auditorium is higher than the laboratory measurements. This was one of the measurements made where strips of carpet in the aisles were removed along with the seats. No sample of this carpet was available to measure separately in the reverberation chamber, so a correction was made using a measurement of a typical carpet sample to hand. It may be that this substituted carpet did not absorb high frequency sound as effectively as the material in hall B1.

C. The modern multipurpose halls C, O, and M

These halls have in common a multipurpose function. As well as, and perhaps partly because of this, they also have in common lightweight chairs and a poor state of diffusion. This has led to problems in predicting the *in situ* absorption coefficient of the seats in two halls. Nevertheless, in the largest of the three, hall C, the agreement between the auditorium and reverberation chamber absorption coefficients is quite good up to 2 kHz, as shown in Fig. 8(a). No reverberation chamber data for the side and front absorption coefficients of these seats were measured, so a "large finite" absorption coefficient cannot be calculated. Because the seats are quite lightly upholstered, and because they are arranged in large blocks in the auditorium, the increase in absorption coefficient due to exposed sides is probably small. Hence a "large finite" line for this hall would not be far above the "infinite" one.

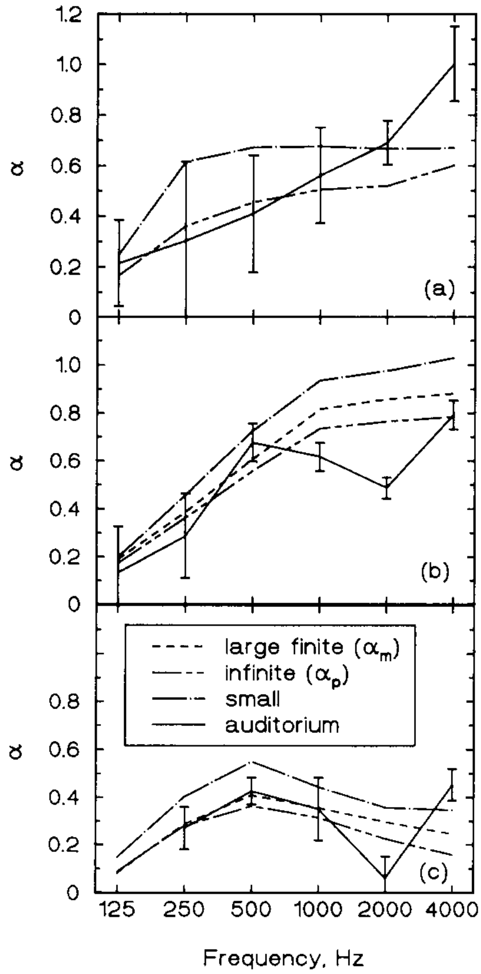

FIG. 8. Absorption coefficient of (a) seating C, (b) seating O, and (c) seating M measured *in situ* and by three different reverberation chamber measurement methods.

In hall C, the auditorium measurement was complicated by the fact that the folding seats were fixed to retractable bleachers. Since neither could be removed from the hall, the "empty" RT measurement was performed with the seats folded down and the bleachers fully retracted, and the "full" measurement with the bleachers extended and the seats erect. The rather high auditorium absorption coefficient at 4 kHz is perhaps due to the unfinished surface of the bleachers themselves absorbing energy when extended.

In Fig. 8(b) the agreement between auditorium and reverberation chamber absorption coefficients for hall O is reasonably good in all frequency bands except 1 and 2 kHz. The same is true of hall M in Fig. 8(c): in both halls the seats seem to absorb little energy at 2 kHz. It is thought these dips may be due to the sound fields in these halls being so badly diffused at 2 kHz that little sound energy actually strikes the seats. This explanation is supported by the observation that decay curves in both halls sagged badly at this frequency.

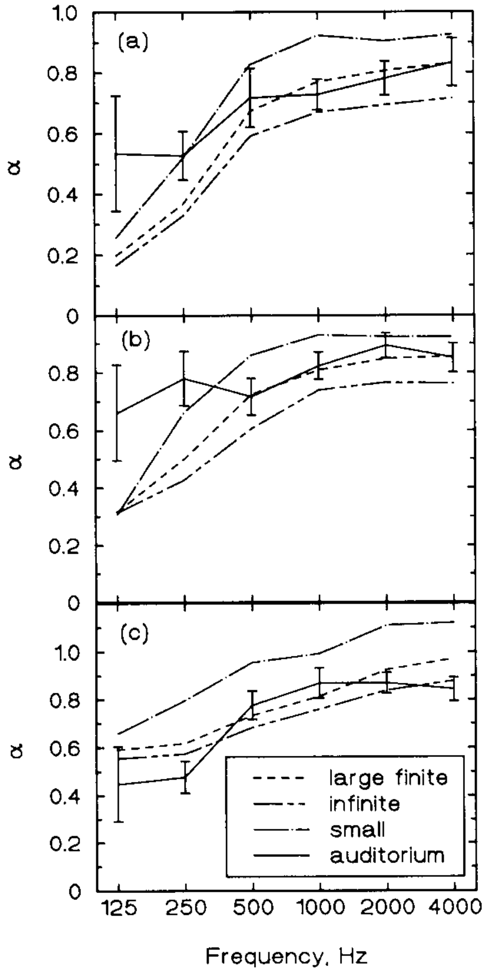

FIG. 9. Absorption coefficient of (a) seating L, (b) seating D1, and (c) seating D2 measured *in situ* and by three different reverberation chamber measurement methods.

D. The theaters D1, D2, and L

In the last group of halls to be investigated, the auditorium calculation is slightly complicated by the problem of the volume of the stagehouse or flytower. Being theatres, all three of these halls have a proscenium arch coupling the volume of the flytower over the stage to the volume of the auditorium where all the seats are installed. The problem was minimized in hall D both before (D1) and after (D2) refurbishment, since the area under the proscenium arch was fairly small and it was covered by a heavy fire curtain during all measurements. It was therefore assumed that the volume of the stagehouse did not play a part in the sound field in the auditorium of hall D. In hall L, conversely, the RT measurements were made during construction. In this theatre, a very large flytower was coupled to the auditorium by a large opening. Since there was no evidence of a dual decay rate in the recorded decay curves, it was assumed that the coupling between the two spaces was perfect, and the volume of the flytower was included in the absorption calculation.

For both theaters L and D1, in Fig. 9, the auditorium absorption coefficient is predicted well by the "large finite" reverberation chamber data for mid and high frequencies. In both cases, the auditorium line is well above the reverberation chamber lines at low frequencies. These discrepancies are similar to the one found for hall *G*, which was also under construction. The reasons seem the same: In hall I approximately 160 m^2 of panelling was probably added during seat installation. This would provide about 80 m^2 of low frequency total absorption and would account for an extra 0.24 in the auditorium absorption coefficient at 125 Hz in Fig. 9(a). Similarly, in hall D1 approximately 110 m^2 of plywood probably introduced an extra 0.23 in the auditorium absorption coefficient at 125 Hz in Fig. 9(b).

The final hall comparison is for theater D2 (D1 after refurbishment) and it appears in Fig. 9(c). This time, the agreement between the "large finite" data and the *in situ* measurement is not quite so good. The match is best at mid frequencies; at low and high frequencies, the reverberation chamber coefficient is too high. The most likely problem at low frequencies is again panelling. This time, about 70 m^2 of wood was probably removed at the time the seats were installed. This would produce a shortfall of about 0.12 in the auditorium absorption coefficient at 125 Hz in Fig. 9(c). At high frequencies, the auditorium field may be less diffuse than that in the reverberation chamber. Table I shows that after refurbishment, the volume per seat of D2 stood at only 3.3 m^3. This is rather less than the 8–10 m^3 commonly used as a rule of thumb for concert halls. It is probable that theater D2 was just too full of highly absorbing seats to achieve a diffuse field at high frequencies.

TABLE II. Percentage difference between reverberation chamber and auditorium absorption coefficients at 1 kHz, compared with the statistical uncertainty in the auditorium data.

Hall	Standard error in auditorium measurement (%)	Difference for "large finite" measurement (%)	Difference for "small" measurement (%)
B2	±7	+4	+27
G	±5	+6	+30
H	±15	−6	+6
B1	±7	−1	+10
O	±10	+32	+52
M	±37	+3	+26
L	±7	+6	+26
D1	±6	−1	+13
D2	±7	−7	+14

E. Midfrequency accuracy

Table II shows the difference between the reverberation chamber and auditorium absorption coefficients at 1 kHz, expressed as a percentage error relative to the auditorium data. In the nine halls for which both "large finite" and "small" data exist, the "large finite" data are almost always much more accurate. Only hall O is a long way off the tentative 5% accuracy requirement. The discrepancy in the "large finite" data for the other halls could perhaps have been reduced by improving the test method, but it is in most cases less than the statistical uncertainty in the auditorium measurement.

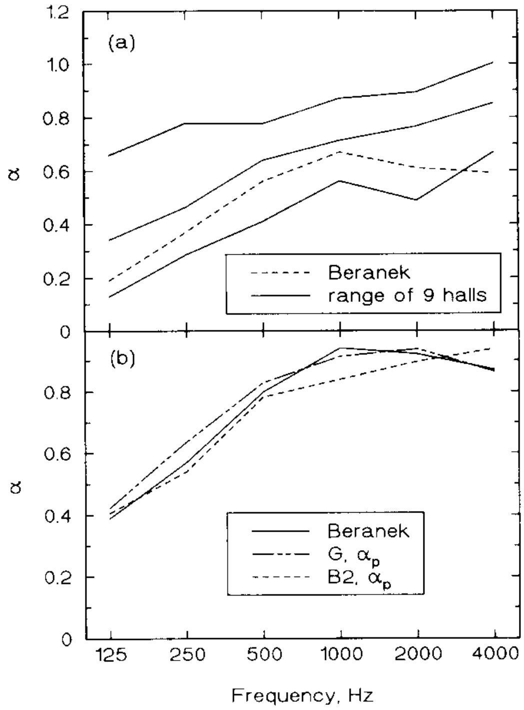

FIG. 10. (a) Minimum, mean and maximum auditorium absorption coefficients for nine unoccupied upholstered seats compared with Beranek's average.[5] (b) Values of α_p for two types of occupied upholstered seats compared with Beranek's average.

F. Comparison with Beranek

Figure 10(a) shows the range of unoccupied auditorium absorption coefficients taken from Figs. 6–9, their mean, and Beranek's data[5] for unoccupied seats. The unusual data from hall M have been excluded. Considering the range of the current data, the agreement between the mean and Beranek's values is quite good up to 1 kHz. At higher frequencies, as Bradley explains,[10] Beranek's absorption data are quite possibly affected by differences in air absorption between the many hall measurements he used. Beranek's data are below the mean of the present data at all frequencies. This may be because modern theatre seating has slightly more padding than the ones forming the bulk of Beranek's data. The spread of data in Fig. 10(a) emphasizes that the use of an average absorption coefficient should be for rough early design figures only, at least for unoccupied RT prediction in a hall.

The comparison of the two sets of occupied data from the reverberation chamber with Beranek's average[5] is very interesting. Figure 10(b) shows that Beranek's coefficient is very close to being the mean of the two measured data sets for seat types B2 and G. Although the occupied data presented here are limited, they point to the possibility that Beranek's average absorption coefficient may be accurate enough to give good predictions of occupied hall RT, at least for some types of seat. This supports the idea that the absorption of occupied upholstered seats is dominated by the absorption of the occupants and so should not vary much over different seat types.

V. CONCLUSION

After validating the barrier method for measuring seating absorption in ten auditoria, it can be concluded that it gave close predictions in eight of them. In all ten halls, ranging from a large modern concert hall to a small theater, any deviations from a good prediction not attributable to random error can be explained by problems in the validation process or hall measurements themselves. These mostly take the form of uncertainties due to the presence of extra absorbing material in the auditorium during the validation. In two halls, a large dip in the auditorium seat absorption coefficient was found that was not predicted by any reverberation chamber measurement. There is evidence that very poor diffusion in the halls was the cause.

In the course of the reverberation chamber measurements, it was found that the use of a frequency-constant edge correction strip could lead to significant errors in auditorium RT prediction. Measurement of the absorption of the front and sides of seats should be used to obtain more accurate estimates. It was also found that the barriers used in the present method could form a resonant low-frequency absorber. The effects of this problem were reduced by making a separate measurement of barrier absorption. Further investigation of the effects of the barrier construction may allow additional reduction of the effect.

In all ten halls, the traditional reverberation chamber measurement method overestimated the *in situ* absorption coefficient. This means that a reverberation time calculation for a new hall based on such a measurement is very likely to give too low a value. Because the overprediction of the traditional measurement is quite large, and the seating is the major absorber in a hall, the deviation from the design value of RT would probably be greater then the subjective difference limen. The present method will also give more accurate results than the use of either Beranek's or Kosten's average absorption data will allow in almost all cases. Finally, the present method achieves an accuracy at least equal to the more lengthy one proposed by Bradley. It is therefore proposed that the optimized barrier method of measuring seating absorption should be adopted for all designs where accurate reverberation time prediction is desired.

ACKNOWLEDGMENTS

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[1] U. Kath and W. Kuhl, "Messungen zur Schallabsorption von Personen auf Ungepolsterten Stuhlen," Acustica **14**, 49–55 (1964).
[2] H. Kuttruff, *Room Acoustics* (Elsevier, London, 1991), 3rd ed.
[3] M. Nagata, "What we have learned from the listening experiences in concert halls—physical properties and subjective impressions of five concert halls in Tokyo," Appl. Acoust. **31**, 29–45 (1990).
[4] L. Cremer and H. A. Muller, *Principles and Applications of Room Acoustics* (Applied Science Publishers, Barking, England, 1982).
[5] L. L. Beranek, "Audience and chair absorption in large halls. II," J. Acoust. Soc. Am. **45**, 13–19 (1969).
[6] C. W. Kosten, "New method for the calculation of the reverberation time

of halls for public assembly," Acustica **16**, 325–330 (1965).
[7] T. Fukuchi and K. Fujiwara, "Sound absorption area per seat of upholstered chairs in a hall," J. Acoust. Soc. Jpn. (E) **6**, 271–279 (1985).
[8] ASTM C 423–84a—"Measurement of sound absorption and sound absorption coefficients by the reverberation room method" (American Society for the Testing of Materials, Philadelphia, 1984).
[9] ISO 354—"Measurement of sound absorption in a reverberation room," (International Organization for Standardization, Geneva, 1985).
[10] J. S. Bradley, "Predicting theater chair absorption from reverberation chamber measurements," J. Acoust. Soc Am. **91**, 1514–1524 (1992).
[11] U. Kath and W. Kuhl, "Messungen zur Schallabsorption von Polsterstuhlen mit und ohne Personen," Acustica **15**, 127–131 (1965).
[12] W. J. Davies, Y. W. Lam, and R. J. Orlowski, "Comment on 'Predicting theater chair absorption from reverberation chamber measurements' [J. Acoust. Soc. Am. **91**, 1514–1524 (1992)]," J. Acoust. Soc. Am. **93**, 2238–2240 (1993).
[13] R. V. Waterhouse, "Interference patterns in reverberant sound fields," J. Acoust. Soc. Am. **27**, 247–258 (1955).
[14] U. Kath and W. Kuhl, "Einfluss von Streuflache und Hallraumdimensionen auf den Gemessenen Schallabsorptionsgrad," Acustica **11**, 50–64 (1961).
[15] W. J. Davies, "The Effects of Seating on the Acoustics of Auditoria," Ph.D. thesis, Salford University, England (1992).
[16] L. L. Beranek, *Music, Acoustics and Architecture* (Wiley, New York, 1962).
[17] A. Lawrence, *Acoustics and the Built Environment* (Elsevier, London, 1989), p. 234.